Applications of Paleolimnology to Sockeye Salmon Nursery Lakes and Ecosystems in the Pacific Northwest and Alaska: Proceedings of a Workshop at the Institute of Ocean Sciences, October 8-9, 2008

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APPLICATIONS OF PALEOLIMNOLOGY TO SOCKEYE SALMON NURSERY LAKES AND ECOSYSTEMS IN THE PACIFIC NORTHWEST AND ALASKA: PROCEEDINGS OF A WORKSHOP AT THE INSTITUTE OF OCEAN SCIENCES, OCTOBER 8-9, 2008

by

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ABSTRACT

MacDuffee, M., and MacIsaac, E. 2009. Applications of paleolimnology to sockeye salmon nursery lakes and ecosystems in the Pacific northwest and Alaska: Proceedings of a workshop at the Institute of Ocean Sciences, October 8-9, 2008. Can. Tech. Rep. Fish. Aquat. Sci. 2847: v + 23 p.

A two-day workshop was convened October 8-9, 2008 to review and synthesize sediment core studies conducted in sockeye salmon *(Oncorhynchus nerka)* nursery lakes in British Columbia, Alaska, and the northwest United States. The objective of the workshop was to advance our understanding of paleolimnological applications and what these techniques can tell us about long-term changes in salmon escapements and lake ecology relative to salmon harvesting and climate change. Seven talks were presented on topics including a background to paleolimnology techniques for salmon nursery lakes, the roles of salmon-derived nutrients in lake ecosystems, the utility and pitfalls of salmon escapement data for referencing sediment core time-series data, and the influence of watershed processes and nitrogen budgets on salmon-derived nutrient signals in lake sediments. Eight talks presented case studies of paleolimnological data from British Columbia and Alaska sockeye salmon nursery lakes and a coastal riparian forest. The workshop concluded with a panel discussion to critically evaluate the potential application of paleolimnological techniques to the management of sockeye salmon. Recommendations were made that define how and where paleolimnological techniques are most likely to contribute to a practical understanding of sockeye salmon ecology and management. These recommendations include the need to formulate questions about sockeye salmon ecology that a paleoecology study of a nursery lake can realistically answer. Preliminary lake nitrogen budgets and consideration of the limitations of historic salmon population data will help determine whether salmon likely leave a detectable $\delta^{15}N$ signal in the sediments. Multi-proxy suites of paleoindicators and an understanding of how sediment deposition and filtering processes alter the sediment record in a given lake are required to interpret variations in sediment signals. A reference lake system and the fitting of nitrogen mixing models are also needed to interpret the $\delta^{15}N$ paleorecord for salmon escapements. Managers need to weigh paleoecological approaches against the costs and constraints of long-term fish population monitoring to be convinced that paleotechniques are worth the investment.

RÉSUMÉ

MacDuffee, M., and MacIsaac, E. 2009. Applications of paleolimnology to sockeye salmon nursery lakes and ecosystems in the Pacific northwest and Alaska: Proceedings of a workshop at the Institute of Ocean Sciences, October 8-9, 2008. Can. Tech. Rep. Fish. Aquat. Sci. 2847: v + 23 p.

Un atelier de deux jours a été tenu, les 8 et 9 octobre 2008, afin d'examiner et de résumer des études sur carottes de sédiments réalisées dans des lacs de séjour du saumon rouge *(Oncorhynchus nerka)* en Colombie-Britannique, en Alaska et dans le nord-ouest des États-Unis. L'atelier visait à faire mieux comprendre les applications paléolimnologiques et ce que ces techniques peuvent nous montrer sur l'évolution à long terme des échappées de saumons rouges et de l'écologie des lacs, en lien avec la pêche au saumon et les changements climatiques. Sept communications ont porté notamment sur l'introduction aux techniques de paléolimnologie dans les lacs de séjour du saumon, sur le rôle des nutriments provenant du saumon dans les écosystèmes lacustres, sur l'utilité et les pièges des données sur les échappées qui servent à référencer les données chronologiques des carottes de sédiments, et sur l'influence des processus des bassins versants et des bilans de l'azote sur les signaux des nutriments provenant du saumon dans les sédiments des lacs. Huit communications ont présenté des études de cas de données paléolimnologiques provenant de lacs de séjour du saumon rouge en Colombie-Britannique et en Alaska ainsi que d'une forêt riveraine côtière. L'atelier s'est conclu par un débat d'experts afin d'évaluer de façon critique l'application possible des techniques de paléolimnologie à la gestion du saumon rouge. Des recommandations ont été formulées en vue de définir comment et dans quels champs d'application ces techniques sont le plus susceptibles de favoriser une compréhension pratique de l'écologie et de la gestion du saumon rouge. Ces recommandations énoncent notamment la nécessité de formuler des hypothèses au sujet de l'écologie du saumon rouge qu'une étude paléoécologique dans un lac de séjour pourrait, de façon réaliste, contrôler. Les bilans préliminaires de l'azote dans les lacs et la prise en considération des limites des données historiques sur les populations de saumons aideront à établir si les saumons laissent vraisemblablement un signal détectable de $\delta^{15}N$ dans les sédiments. Des ensembles multiples de paléoindicateurs de substitution ainsi qu'une bonne compréhension de la façon dont le dépôt et la filtration des sédiments modifient les relevés d'un lac sont nécessaires pour interpréter les variations dans les signaux des sédiments. Un réseau de lacs de référence et le calage des modèles de mélange de l'azote sont également essentiels pour interpréter les relevés paléontologiques de $\delta^{15}N$ concernant les échappées de saumons. Pour se convaincre qu'il vaut la peine d'investir dans les techniques paléoécologiques, les responsables doivent mettre celles-ci en balance avec les coûts et les contraintes de la surveillance à long terme des populations de poissons.

INTRODUCTION

Paleolimnology is the multidisciplinary study of lake sediments as potential archives of the physical, chemical and biological histories of lakes and their watersheds. Lake sediment cores, like tree rings and ice cores, have proven to be important long-term records of natural variations and anthropogenic disturbances in terrestrial and aquatic ecosystems. They have been used to reconstruct histories of regional and global climate variations, air-borne and watershed pollutant influxes, and changes in the productivity, ecology and species succession of forests and lakes (Hall and Smol 1992, Lockhart et al. 2000, Walker and Pellat 2004).

The sediments of sockeye salmon (*Oncorhynchus nerka*) nursery lakes have been studied over the years for temporal variations in lake nutrients, productivity and trophic processes (Donaldson 1967, Stockner and Costella 1980, Edmondson 1991, Kerfoot 1995). However there has been a recent surge in the use of paleolimnological techniques in the Pacific Northwest and Alaskan sockeye lakes after the discovery that ratios of stable nitrogen isotopes showed promise as indicators of salmon escapements to nursery lakes (Finney 1998). Anadromous sockeye salmon spawn, often in high numbers, in the tributary streams and beaches of lakes that serve as rearing areas for their progeny. Their spawning seeds the rearing lake with planktivorous fry and enriches the streams and lake with carcass organic matter and nutrients largely derived from marine sources. The marine-derived nitrogen in salmon carcasses is enriched with the ^{15}N stable isotope of nitrogen relative to other freshwater and terrestrial nitrogen sources (Kline et al 1990), and has now been used in paleolimnological studies to reconstruct pre-historical time series of salmon escapements to various sockeye lakes (Finney et al 2002, Gregory-Eaves et al. 2004, Selbie et al. 2007).

Other studies were not as successful using $\delta^{15}N$ to reconstruct sockeye escapements to lakes (Holtham et al. 2004, Hobbs and Wolfe 2007, 2008). High flushing rates, high terrestrial organic nitrogen loadings and low and invariant sedimentary $\delta^{15}N$ levels were cited as problems masking salmon nitrogen signals in the sediments. There were also concerns about the quality and biases of the salmon escapement data being used to calibrate $\delta^{15}N$ mixing models (Tschaplinski and Hyatt 1991). These studies all suggested that there are constraints on where paleolimnological techniques can provide useful information on past sockeye abundances and nursery lake ecosystem processes. Other studies have shown promise using alternative or complementary proxies such as diatom abundances, algal pigments and cladoceran zooplankton remains to infer changes in salmon abundance (Gregory-Eaves et al. 2003, Sweetman and Finney 2003, Schindler et al. 2005).

The paleolimnological research was clearly at a stage where it would be advantageous to review the published and unpublished science conducted to date and to convene a workshop and panel of experts to discuss the techniques, problems and interpretations of the data towards making recommendations about how and where paleolimnological techniques could best be applied to sockeye systems. If paleolimnological techniques can reconstruct reliable long-term histories of salmon escapements, fry densities, zooplankton food resources, nutrient loading and lake productivity, they will greatly improve our knowledge of sockeye salmon ecosystem processes and management of the stocks.

WORKSHOP OVERVIEW

Goals & Structure

We convened a two-day workshop on October 8-9, 2008 at the Fisheries and Oceans Canada Institute of Ocean Sciences, Sidney, BC, to review and synthesize many of the sediment core studies that have been conducted in sockeye salmon nursery lakes in British Columbia, Alaska, and the northwest United States. The objective of the workshop was to advance our understanding of paleolimnological applications and what these techniques can tell us about long-term changes in salmon escapements and lake ecology relative to salmon harvesting and climate change. The workshop consisted of a series of invited talks followed by a moderated panel discussion to explore issues and make recommendations about the applicability of paleoecology techniques to reconstructing salmon escapements and understanding sockeye lake ecosystems.

The workshop was hosted by the Raincoast Conservation Foundation and Fisheries and Oceans Canada with funding from the Northern Boundary Fund of the Pacific Salmon Commission. Additional sponsorship was provided by the Watershed Watch Salmon Society. All talks were recorded and many have been posted to the events section at http://www.raincoast.org.

AGENDA

Setting the Stage

Paleolimnological techniques: What can lake sediments tell us about past salmon abundance? Irene Gregory-Eaves, Department of Biology, McGill University

Shared Objectives and Issues for Wild Salmon Policy and Paleolimnology. Kim Hyatt, Fisheries and Oceans Canada, Science Branch, Pacific Biological Station, Fisheries and Oceans Canada

The importance of salmon-derived nutrients on lake ecosystems. Peter Leavitt, Canada Research Chair in Environmental Change and Society, Department of Biology, University of Regina

Biogeoclimatic influences on the reconstruction of sockeye salmon abundance from lake sediments. Daniel T. Selbie, Fisheries and Oceans Canada, Science Branch, Cultus Lake Salmon Research Laboratory, Cultus Lake, BC

Translating variation in sediment $\delta^{15}N$ into pre-historical salmon population dynamics. Daniel Schindler, School of Aquatic and Fishery Sciences, University of Washington

Marine-Derived Nutrients & Trophic Interactions

The fate of salmon-derived nutrients: Insights from lake studies in Alaska. Bruce Finney, Department of Biological Sciences, Idaho State University

Long-term food web dynamics in sockeye nursery lakes of Alaska. Guangjie Chen, Department of Biology, McGill University

Lake Case Studies and Reconstructions

Paleoindications of long-term escapement, watershed, human and climate disturbances to the rearing environments of sockeye salmon in Quesnel and Shuswap Lakes. Erland MacIsaac, Science Branch, Fisheries and Oceans Canada, Cooperative Resource Management Institute, Simon Fraser University

Recent paleolimnology of three salmon nursery lakes in the Fraser River Basin. Will Hobbs, Department of Earth and Atmospheric Sciences, University of Alberta

What do tree cores tell us about past salmon abundance in the watersheds of Owikeeno Lake, Rivers Inlet, British Columbia? Tom Reimchen, Department of Biology, University of Victoria

Preliminary findings from Owikeeno Lake sediment cores, Rivers Inlet, British Columbia. Misty MacDuffee, Raincoast Conservation Foundation

Not wanted on the voyage - biovector contaminant transport and lake sediment records. Robie Macdonald, Institute of Ocean Sciences, Fisheries and Oceans Canada

Recent influence of sockeye abundance and climate change on paleolimnology of Kitlope Lake, British Columbia. Aaron Hill, Hillfish Consulting

The utility of paleoecology and sedimentary $\delta^{15}N$ as indicators of past salmon abundance in coastal British Columbia. Marlow Pellatt, Parks Canada, Western and Northern Service Centre

Changes to the productivity and trophic structure of a sockeye salmon rearing lake in British Columbia. Janice Brahney, Environmental Biogeochemistry Lab, University of Colorado

Sockeye salmon nursery lakes and sedimentary $\delta^{15}N$ in southeast Alaska. Dave Barto, Alaska Department of Fish and Game

Panel Discussion

Moderator: Erland MacIsaac
Panel Participants: Bruce Finney, Daniel Selbie, Peter Leavitt, Dan Schindler, Kim Hyatt

Panel Focus: Panellists were asked to provide their opinions on key questions arising from the workshop.

INVITED TALKS

Setting the Stage

Paleolimnological techniques: What can lake sediments tell us about past salmon abundance?
Irene Gregory-Eaves, Department of Biology, McGill University

The myriad of stressors on Pacific salmon populations, together with the large inter-annual variability in numerous salmon stocks, present serious challenges to

managing these fish in a sustainable fashion. To address these challenges, the DFO's Wild Salmon Policy has set out to develop long-term biological targets, along with several other initiatives. As a paleolimnologist, I read this policy statement and the organization of this symposium as an opportunity for collaboration and a sign of interest in the work published on paleolimnological reconstructions of past salmon population dynamics. One only has to recall the great environmental success story of acid rain mitigation to see that collaborations between paleolimnologists and environmental managers can bear significant fruit. Strong science, management and collaboration, however, all require a frank dialogue about the strengths and limitations of different approaches. The aim of this talk will be to provide a primer on how one can apply paleolimnological techniques to reconstruct past salmon population dynamics, to review some of the exciting findings that have been noted thus far, and to discuss some of the limitations of this technique and the directions in which it could be further developed.

Shared Objectives and Issues for Wild Salmon Policy and Paleolimnology
K. Hyatt, Fisheries and Oceans Canada, Science Branch, Pacific Biological Station, Nanaimo, B.C.

Canada's Wild Salmon Policy (WSP) shifts the focus from managing for harvest of maximum sustainable yield towards managing for a better balance between harvest, stock conservation and maintenance of regional biodiversity. Implementation of the WSP and paleo-studies of sockeye salmon lakes share some common objectives and issues. Escapement data is used by both the WSP and paleo-studies to examine the impacts of ecosystems on salmon and the impacts of salmon on ecosystems. However informed use of escapement data is critical. Enumeration methods vary widely among populations and over time. Assumptions about the constancy of survey methods, standards and effort, escapement timing and count efficiencies are often not valid.

Pacific Rim freshwater ecosystems are energy and nutrient limited and an objective of both the WSP and many paleo-studies is to consider the role that salmon marine-derived nutrients play in ecosystem processes. A key WSP ecosystem objective is to maintain the productive capacity of habitats for salmon and, where critical, salmon-dependent contributions of nutrients and energy that influence aquatic ecosystem structure and productivity.

Paleo-studies could contribute to WSP objectives by identifying key reference state conditions for freshwater ecosystems supporting sockeye salmon:

- historic and prehistoric changes in salmon abundances and their effects on freshwater food-webs and productivity
- clarify the role of naturally induced disturbance events or regimes (NIDER) versus human induced disturbance events or regimes (HIDER) on ecosystem integrity and salmon abundance variations.
- develop reliable paleo-indicators for each of the above

There are several challenges and additional research needs that must be met to increase the relevance of paleo-studies to salmon management and the WSP objectives:

- uncertainties remain about the general utility of paleo-study results and their interpretation
- uninformed applications of escapement data
- the confounding effects of top-down salmon predation and bottom-up carcass nutrients on paleo-indicators of foodweb and productivity conditions

- temporal and spatial variations in paleo-indicators and their interpretation (e.g. clarity of MDN signatures in Alaska vs BC lakes)
- uncertainty regarding the extent to which fossil taxa reflect dominant versus marginal processes and species interactions without contemporary supporting observations

The importance of salmon-derived nutrients on lake ecosystems.
Peter Leavitt, Canada Research Chair in Environmental Change and Society, Department of Biology, University of Regina

L. Bunting, D.E. Schindler, B.P. Finney, I. Gregory-Eaves, D.T. Selbie, G. Chen, M.G. Pellat, and D.G. Bos,

Recent research in Alaskan salmon nursery lakes demonstrates that variation in fisheries escapement and the associated influx of marine-derived nutrients (MDN) regulates primary production of natal ecosystems. However, less is known about the relationship between MDN influx and algal production in lakes south of Alaska. To address this shortcoming, historical changes in nitrogen (N) input (as sedimentary $\delta^{15}N$) and algal abundance (as fossil pigments) were compared with nutrient mass balances for 31 lakes with salmon and 15 reference sites from Alaska (AK), British Columbia (BC) and Washington (WA) to quantify the spatial and temporal variability of lake primary production and the relationship between historical changes in salmon and algal abundance. Sedimentary $\delta^{15}N$ signatures increased from coastal to inland sites at low latitudes independent of salmon presence or density. Unlike nursery lakes in AK, MDN accounted for <10% of total ecosystem nutrient influx in BC and WA lakes, and past algal production varied independently of salmon escapement in both these regions. Further, in these natal lakes, the diversion of MDN subsidies to commercial harvest had no measurable effect on ecosystem productivity.

Biogeoclimatic influences on the reconstruction of sockeye salmon abundance from lake sediments.
Daniel T. Selbie, Fisheries and Oceans Canada, Science Branch, Cultus Lake Salmon Research Laboratory,

Early applications of paleolimnology in Alaska demonstrated a remarkable potential for understanding the long-term population dynamics of Pacific salmon from lake sediments. Subsequent studies from other nursery systems, however, have yielded mixed success in detecting discernable salmon-derived nutrient (SDN) signals. This variance has been broadly attributed to a suite of exogenous and endogenous factors inherent to the diversity of sockeye salmon nursery habitats.

The integration of previous studies with a new analysis of sediments across 56 salmon lakes in Canada and the USA, demonstrates that climatic, physiographic and landscape vegetation features are likely important modifying controls on the incorporation of salmon nutrients in lake sediments. These processes likely modify sedimentary geochemical and biological microfossil composition, through variation in nutrient source contributions as well as hydrological and possibly chemical mechanisms which regulate the biological attenuation and incorporation of SDN in lake sediment records.

The influence of these modifying processes and alternate nutrient sources necessitates the consideration of sedimentary records in salmon nursery lakes within a 'mass-balance' context. Site selection that maximizes the relative importance of SDN to

lake nutrient budgets and the use of multi-proxy approaches and control (i.e. non-salmon) sites appear to be crucial in identifying problematic records or periods within temporal sequences.

Translating variation in sedimentary $\delta^{15}N$ into pre-historical salmon population dynamics.

Daniel Schindler, School of Aquatic and Fishery Sciences, University of Washington,

Interest in using paleolimnological techniques to estimate pre-historical salmon abundances has grown substantially in the past decade. Such methods offer hope for estimating abundances of salmon (particularly sockeye salmon) prior to commercial fisheries and extensive development of watersheds. Paleo approaches also provide a means to estimate the variability in salmon stocks prior to the intensification of a variety of other industrial human activities that affect salmon population dynamics.

Nitrogen stable isotope ratios offer the most direct link between salmon abundance and sedimentary records because salmon transfer isotopically-unique nitrogen from the ocean to sockeye salmon nursery lakes and these salmon-derived nutrients can be a substantial component of the nitrogen budget of these lakes. However, with a few exceptions, most published studies using $\delta^{15}N$ have misused this indicator of salmon-derived nutrients to infer pre-historical salmon abundances. In particular, most studies have not realized that salmon abundance is not linearly related to sedimentary $\delta^{15}N$; the value of sedimentary $\delta^{15}N$ must asymptote at the value of salmon $\delta^{15}N$ (plus any fractionation) as salmon-derived nutrients become an increasing proportion of the nitrogen budget of nursery lakes. Thus, assuming that the relationship between salmon abundance and sedimentary $\delta^{15}N$ is described by a linear relationship results in underestimates of pre-historical salmon abundance, and this bias becomes increasingly large as salmon abundance increases. A second problem with previous paleo-salmon studies is that there has been no consideration for fractionation effects on sedimentary $\delta^{15}N$. When N is at high concentrations, algae should fractionate against ^{15}N thereby producing a depleted sedimentary signal relative to the sources of N available to algae. In addition, denitrification in the water column and in the sediments will enrich sedimentary $\delta^{15}N$. What complicates these relationships is that salmon load nutrients at a relatively low N:P ratio, which should produce decreasing fractionation as salmon abundance increases. There have been no systematic analyses to determine how this combination of potential fractionations may affect interpretation of sedimentary $\delta^{15}N$. However, preliminary meta-analyses I have done with published sedimentary $\delta^{15}N$ data suggest (luckily!) that these fractionation effects are minimal. The last, and probably the most important, consideration for interpreting sedimentary $\delta^{15}N$ is the problem that the rate of watershed N loading determines the degree of sedimentary ^{15}N enrichment at a given salmon abundance. All previous studies using paleo-salmon techniques have assumed that watershed N loads are static. This is clearly an important assumption as increased watershed N loads dilute the effects of salmon on the combined $\delta^{15}N$ of sediments, and vice versa. Therefore, future attempts to reconstruct pre-historical salmon abundances should account for changes in background N loading (independent of salmon) to properly assess salmon population dynamics. Given the potential influence of such paleo-reconstructions on management, managers, fishermen, and wildlife, there is substantial responsibility on paleolimnologists to properly interpret paleolimnological indicators of pre-historical salmon abundance.

Marine-Derived Nutrients & Trophic Interactions

The fate of salmon-derived nutrients: Insights from lake studies in Alaska.
Bruce Finney, Department of Biological Sciences, Idaho State University,

Marine-derived nutrients (MDN) transported by salmon into freshwaters when they return to spawn may be an important control on salmon production. If so, there may be feedbacks between escapement, aquatic productivity and subsequent salmon production affected by climate and commercial fishing. To better understand these processes, the University of Alaska Fairbanks and the Alaska Department of Fish and Game developed a project to examine the role of MDN in lake productivity by integrating studies of nutrient cycling, primary productivity, zooplankton, juvenile sockeye and stable isotopes. We utilized detailed and contemporaneous sampling of the water column in anadromous Karluk and control Spiridon Lakes on Kodiak Island. Results show significantly higher levels of total phosphorus, chlorophyll *a*, primary productivity, zooplankton biomass in Karluk relative to Spiridon. Average $\delta^{15}N$ values for lake POM, zooplankton and sockeye smolts are more than 4‰ higher in Karluk than Spiridon. The enhanced nutrients, plankton biomass and productivity in the anadromous system, coupled with $\delta^{15}N$ enrichment in biota and differing seasonal patterns, are consistent with a positive influence of MDN on productivity. Ultimately, it is hoped that such data will provide a framework for long-term monitoring of such marine-terrestrial linkages.

Long-term food web dynamics in sockeye nursery lakes of Alaska.
Guangjie Chen, Department of Biology, McGill University,

Long-term food web dynamics in salmon nursery systems can help us to understand ecosystem functioning and biodiversity, and therefore help maintain sustainable fisheries in the Northeast Pacific. A significant factor structuring limnetic communities in at least a few sockeye salmon nursery lake systems are the salmon-derived nutrients (SDN, measured as $\delta^{15}N$). Several studies have argued, however, that SDN are of little importance in some nursery lake systems. For this talk, we will present analyses of sedimentary records from six Alaskan lakes to define how spawning sockeye salmon affect limnetic primary and secondary producers across a modern gradient of sockeye salmon escapement densities. As expected, we detected a strong correspondence between diatom inferred total phosphorus (TP) trends and $\delta^{15}N$ in lakes that had high and variable $\delta^{15}N$ signatures, suggesting that salmon-derived nutrient (SDN) loading was driving the total nutrient budget in these lakes. Across lakes we found that the amplitude of variation in salmon-derived nutrients (SDN) had a significant and positive influence on diatom species turnover (beta-diversity). A bottom-up effect that scaled with the intensity of SDN dynamics was also evident in long-term secondary production records (represented by *Bosmina* flux): very low levels of SDN showed little impact on both trophic levels, but SDN enhancement effects were clear in lakes with a strong input of SDN. The salmon-zooplankton interaction, however, is also characterized by other biotic processes, including top-down control. Two *Bosmina* species with different body sizes showed differential size responses to predation pressure, where the smaller *B. longirostirs* is more sensitive to invertebrate predation and large-bodied *B. longispina* is more vulnerable to predation by juvenile sockeye. In all, the predator-prey dynamics revealed in this study suggest that the focus on unidirectional nutrient and energy flows along food webs in salmon ecosystems may underestimate the complexity in biotic interaction in food webs. A further analysis of the food web dynamics, linking both empirical (paleolimnological, limnological) and experimental methods, can broaden our understanding of community and ecosystem dynamics, and help define management policies for sustainable fisheries.

Lake Case Studies and Reconstructions

Paleoindications of long-term escapement, watershed, human and climate disturbances to the rearing environments of sockeye salmon in Quesnel and Shuswap Lakes.

Erland MacIsaac, Science Branch, Fisheries and Oceans Canada, Cooperative Resource Management Institute, Simon Fraser University

Shuswap and Quesnel lakes are two large, multi-armed lakes that are the spawning and juvenile rearing habitats of a large portion of the sockeye salmon runs in the Fraser River watershed. The different arms of the lakes support different sockeye spawning populations that have been impacted to varying degrees since the late 1800's by intense commercial fishing, migration barriers, watershed development and industrial impacts on spawning habitats. The purpose of this study was to determine whether paleoindicators from sediment cores recorded the history of salmon escapements and anthropogenic impacts and whether lake productivity and zooplankton forage levels in these nursery lakes have changed over time.

Sediment cores were collected from 4 arms of Shuswap Lake and 2 arms of Quesnel Lake in basins near major sockeye spawning rivers as well as at mid-lake reference stations well away from spawning rivers. Salmon carcass abundance was tracked in the sediments using the $\delta^{15}N$ stable isotope of nitrogen while phytoplankton production was assessed using total phaeophytin levels. Sub-fossils of cladoceran zooplankton were used as an index of zooplankton abundance and the population size of planktivorous juvenile sockeye. Cores were dated using ^{210}Pb techniques.

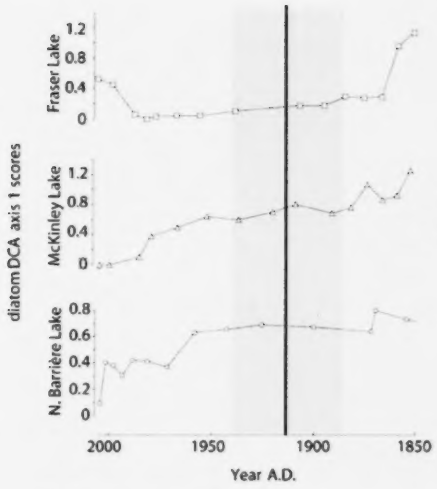
All the cores record a variety of anthropogenic effects on these sockeye nursery lakes including the effects of overfishing and migration blockages on sockeye escapements, sediment generation in the watersheds from agriculture, mining and forestry, and nutrient loading from agriculture and settlement in the drainage basins. Most sediment cores from Shuswap Lake showed the effects of the 1913/14 Hell's gate slide on sockeye escapements to the major spawning streams with marked declines in $\delta^{15}N$ levels in the sediments and increased cladoceran abundances released from grazing pressure. The Seymour Arm cores also provided a unique 1200-yr record of long-term variations in sockeye escapements that likely reflect long-term climate changes. Phaeophytin and cladocera abundance co-varied with $\delta^{15}N$ levels, indicating that the productivity of Seymour Arm has been historically dependent on nutrient loadings from summer-run sockeye carcasses. Recent sediments off the Adams and Salmon Rivers also demonstrate the chronic effects of local land-use activities (agriculture, sewage, septic) in the last century on nutrient loadings to Shuswap Lake. ^{15}N from human sources has masked the salmon signal in the last 50 years.

The Quesnel Lake cores from off the Horsefly River show the impacts of human activity in the watershed since the start of hydraulic placer mining in the 1870s. Increased sediment inputs and loadings of ^{15}N-rich nitrogen from ranching land-use in the Horsefly drainage swamp the recent salmon carcass $\delta^{15}N$ signal. However cores collected from the north arm of Quesnel Lake show a gradual decline in $\delta^{15}N$ from before the turn of the century rather than the abrupt drop expected after Hells Gate. A significant change has occurred in the cladoceran zooplankton community of the north arm over the last several decades with a shift from Daphnia dominance to Bosmina dominance. The shift suggests a fundamental change has occurred in the structure of

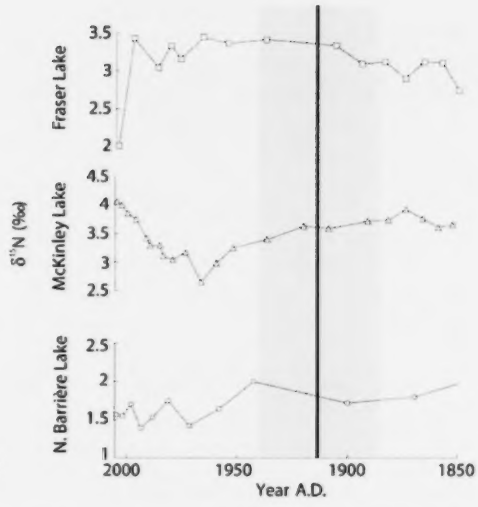
the planktonic foodwebs in Quesnel Lake that may have implications for juvenile salmonids.

Recent paleolimnology of three salmon nursery lakes in the Fraser River Basin.
Will Hobbs, Department of Earth and Atmospheric Sciences, University of Alberta

The use of paleolimnology to reconstruct the collapse of the Fraser River sockeye salmon (*Oncorhynchus nerka*) populations following the landslides at the Hells Gate section of the Fraser canyon (British Columbia, Canada) is explicitly tested. Construction of the Canadian Pacific Railway caused a series of landslides in 1913–1914, partially blocking the Fraser River, preventing spawning salmon migration, and causing a near-complete collapse of upstream salmon stocks. We selected three sockeye nursery lakes upstream of Hells Gate, which varied in spawner density, migration length, and lake catchment characteristics. In each of the lakes, geochemical (stable nitrogen isotopes and C:N) and biological (diatoms) proxies failed to register the impact of a dramatic decrease in marine-derived nutrients (MDN). Additional variations in sockeye abundance, documented by the onset of commercial fishing and modern escapement records, were also not imprinted on the sediment record. Changes in diatom assemblages are coincident with 20th century climate warming and local catchment disturbances and are not attributable to variability in MDN subsidies. These results suggest that MDN do not remain within lakes in the Fraser River drainage long enough to become faithfully archived in the sediment record or that the lakes do not receive sufficient MDN to produce a recognizable sedimentary signature.



A) Summary of diatom compositional change in three BC salmon nursery lakes as measured by detrended correspondence analysis of diatom relative percent data. Units are standard deviations, where compositional shifts are relative to the amount of change between samples.



B) Summary of sedimentary $\delta^{15}N$ in the same nursery lakes. The vertical line represents the Hells Gate slides of 1913-1914 and the shaded area is the estimated 210Pb CRS age model uncertainty. No significant changes in diatom assemblages or $\delta^{15}N$ are expressed following the Hells Gate induced salmon crashes.

What do tree cores tell us about past salmon abundance in the watersheds of Owikeeno Lake, Rivers Inlet, British Columbia?
Tom Reimchen, Department of Biology, University of Victoria

Estimating historical abundance of salmon returning to coastal rivers and lakes continues to challenge fishery researchers. I summarize recent results of stable isotope signatures from yearly growth rings of ancient trees adjacent to three salmon rivers (Amback, Ashlulum, Dallery) and a control site (Doos) entering Owikeeno Lake. Doos River had the lowest $\delta^{15}N$ values among the four watersheds. Isotopic signatures are highly variable over time within watersheds and show limited historical consistency among trees (1880-1980) although there are broad concordant trends between $\delta^{15}N$ tree signatures and lake core signatures (data from MacDuffee). More recent isotopic data from growth rings of these trees indicate large intra-year fluctuations in signatures. While this is unexpected given the horizontal translocation of nitrogen among rings, these data potentially allow novel and improved resolution for identifying seasonal trends in nutrient cycling. However, various physiological and edaphic issues remain to be resolved before meaningful salmon signatures can be extricated from the remaining ancient trees that still persist in some of the Owikeeno watersheds.

Preliminary findings from Owikeeno Lake sediment cores Rivers Inlet, British Columbia.
Misty MacDuffee, Raincoast Conservation Foundation

Owikeeno Lake is a glacially turbid, oligotrophic nursery lake in Rivers Inlet, BC that supported a total sockeye population of one to three million between 1948 and 1974, and an average catch of one million 1884-1974. A decline in abundance began in the late 1970s and collapsed to 3600 spawners by 1999. The population has not recovered above 150,000. Sediment cores extracted from the less glacial upper basins in 2004 were analyzed for geochemical proxies. Diatom and zooplankton microfossils were surveyed but virtually absent. CN ratios averaging 18:1 indicate a strong terrestrial influence on organic matter. Despite this, both $\delta^{15}N$ and $\delta^{13}C$ show weak but significant correlations with fluctuating escapement trends over the 20thcentury and a decline from the 1980s onward. There is no obvious change in $\delta^{15}N$ corresponding to the start of the commercial fishery. A positive correlation existed between sockeye escapement and Wannock River discharge and a negative correlation between escapement and air temperature. C:N ratios were negatively correlated with temperature and PDO. A mixing model suggests that prior to the mid 1980s, roughly 22% of the nutrients in Owikeeno Lake were salmon derived. While additional proxies are needed to reduce geochemistry ambiguities, the preliminary findings suggest a decline in lake productivity may have occurred in the last 25 years. Light however, may still be a larger limiting factor on lake productivity. The degree to which these and other climate conditions combine to impact extremely low salmon abundance requires expanded analysis and investigation.

Not wanted on the voyage - biovector contaminant transport and lake sediment records.
Robie Macdonald, Institute of Ocean Sciences, Fisheries and Oceans Canada
JM. Blais, E. Kruemmel, LE. Kimpe, I Gregory-Eaves,

It is well known that salmon deliver marine nutrients to natal lakes, often making a trip of over 1000 km across a large river system to do it. It is less well known that salmon also accumulate and concentrate fat-soluble contaminants at a relatively high trophic-level (3-4) and return these as well. Over the past 7 years, we have collected sediment cores from numerous lakes extending between Southern BC to Alaska where historical salmon escapements are known to determine the impact of sockeye salmon on contaminant exposures in such lakes.

Our findings show that for lakes receiving the largest density of salmon return (numbers/hectare) the burden of PCB can outweigh atmospheric delivery by almost a factor of 10. Clearly, the fish themselves become the important vector for contaminant exposure into their life cycle, and this sort of exposure will decrease at a rate determined by global PCB cycling between large reservoirs in terrestrial soils and plants and in the upper ocean. Initially, we hypothesized that contaminant records in sediments from individual lakes might imitate recent (post 1950) variations in salmon return densities. We were wrong; the system of delivery, transfer, and sedimentation interacts with productivity drawdown that renders simple relationships between escapement, PCB flux and $\delta^{15}N$ records in sediments complicated.

Recent influence of sockeye abundance and climate change on paleolimnology of Kitlope Lake, British Columbia.
Aaron Hill, Hillfish Consulting

Paleolimnological studies of sockeye salmon (*Oncoryhynchus nerka*) nursery lakes have shown that lake trophic status is often regulated by climate and harvest via marine-derived nutrients (MDN) from adult spawners. However, these controls are not well understood for sockeye nursery lakes in coastal British Columbia (BC), many of which are ultraoligotrophic and glacially turbid. We examined climate, sockeye population dynamics, and sedimentary indicators of lake algal production from 1958–2005 using a radioisotope-dated sediment core from Kitlope Lake, BC. Despite high sedimentation rates (~4.7 mm yr^{-1}), significant influence of terrestrial and aquatic organic matter from the main tributary, and the lowest mean (± SD) $\delta^{15}N$ (-0.28 ± 0.79 ‰; a proxy for MDN flux) yet reported from a sockeye nursery lake, sedimentary $\delta^{15}N$, C/N, and fossil pigments were coherent with order-of-magnitude changes in sockeye escapements. Moreover, air temperatures were positively correlated with $\delta^{15}N$, indicating a climate influence counteracting declines of MDN import related to declining spawner returns. Despite elevated production potential, Kitlope Lake remains nutrient limited with a declining sockeye population, and the productivity of this system would benefit from increased sockeye returns.

The utility of paleoecology and sedimentary $\delta^{15}N$ as indicators of past salmon abundance in coastal British Columbia.
Marlow Pellatt, Parks Canada, Western and Northern Service Centre.

Pacific Salmon (*Oncorhynchus* species) are important components of North Pacific ecosystems and serve as a food resource, keystone species, and as a cultural icon for First Nation's people. Over the last century declines in salmon numbers due to fishing, habitat destruction, and possibly global climate change has resulted in habitat restoration projects and the listing of some salmon populations as endangered. Parks Canada has a mandate to maintain the ecological integrity of terrestrial and marine ecosystems in representative regions within Canada and its national waters. In order to understand the ecological integrity of any given ecosystem it is essential to understand the natural range of variability in which the system exists as well as the impact people and climate change have had on it. It has been identified that a better understanding of long-term salmon abundance is necessary to adequately manage these species. Recent paleolimnological analysis of sockeye salmon (*Oncorhynchus nerka*) rearing lakes using diatoms and stable isotope analysis has shown some promise as a tool to examine past salmon abundance. Successful studies have been published using $\delta^{15}N$ as an indicator in Alaska, British Columbia, and Idaho.

This study presented here is a multiproxy investigation that uses paleoecological methods to reconstruct environmental conditions for the last ~300 years in three lakes and their watersheds on the west coast of Vancouver Island. Pollen, diatoms, cladocera, sediment, and stable isotope analyses of ^{210}PB dated sediments from lakes in or near Pacific Rim National Park Reserve of Canada reveal changes in forest structure, limnological conditions, and salmon populations. This paper will also describe research undertaken at a number of sockeye salmon bearing lakes along the coast of British Columbia, Canada (mainland and adjacent islands) using stable isotope analysis and paleolimnology. The results of this research program contribute to our understanding of the role of marine derived nutrients in regard to lake productivity along the west coast of North America. This research indicates that while salmon derived nutrients may be of key importance in juvenile salmonid development in some lakes, this may not be the case in all systems, especially those in which flushing rates are high. In these systems diatom communities appear to be more sensitive to fluctuations in salmon populations than stable isotope methods, provided that other changes in trophic status are minor. The role of this type of research in ecosystem management is important to Parks Canada and the utility of δ^{15}N in understanding the complexities of land sea interactions and the interplay between terrestrial and marine protected areas will be discussed.

Changes to the productivity and trophic structure of a sockeye salmon rearing lake in British Columbia.
Janice Brahney, Environmental Biogeochemistry Lab, University of Colorado.

In the 1990's, sockeye salmon (*Oncorhynchus nerka*) returns to Long Lake in Smith Inlet, British Columbia declined substantially. In 1997 the commercial fishery was closed and will not be reopened until the population shows signs of sustained recovery. Here we present results from a sediment core extracted from Long Lake in 2002. Nitrogen isotope concentrations (δ^{15}N) in the sediment core declined in the 20th century to unprecedented levels. Sodium and other alkali elements also decreased at a generally accelerating pace since the mid-nineteenth century, and there are indications that the headwater glacier receded apace. Accompanying these trends, were notable changes in proxies for lake ecology including sediment organic concentrations and *Bosmina* flux, carapace length, and mucro length. The timing and behavior of these unprecedented changes in the sedimentary record points to potential impacts from both commercial fishing and climate change.

Sockeye salmon nursery lakes and sediment δ^{15}N in southeast Alaska.
Dave Barto, Alaska Department of Fish and Game.

Recent studies have demonstrated that the historical distribution of δ^{15}N in lake sediments can be a useful proxy in reconstructing salmon abundance trends. Although this proxy data cannot describe current salmon stock status, it can be useful in placing the current abundance trends in context. Information generated from long-term changes in fish abundance can provide insight into natural ecosystem variability, the impact of human disturbance, and useful information for sustainable fisheries management.

Glacial lakes in northern Southeast Alaska and the Taku River are important contributors to the local commercial sockeye salmon harvests in both the US and Canada. Sediment cores were collected and analyzed from Chilkoot, Little Trapper, Tatsamenie and Trapper lakes for this study. The results indicate that salmon MDN are an important nutrient source in these glacial nursery lakes. However, the glacial influences coupled with relatively low escapements presented δ^{15}N analytical challenges. The results indicate that sediment percent nitrogen and

$\delta^{15}N$ are low. Average sediment $\delta^{15}N$ and percent nitrogen values ranged from +1.6 to +2.6 and 0.01 to 0.06 respectively. However, these results are quite variable between subsamples at all of the study sites.

In addition to ^{137}Cs and ^{210}Pb radioisotope dating, thin section varve dating methods were employed at three of the study sites. Varve chronologies and the sedimentary signal from some, if not all of these lakes can help explain the timing of the observed proxy changes.

PANEL DISCUSSION SUMMARY

An experts panel was convened after the presentations to explore issues arising from the talks and allow audience participants to pose questions. The panel consisted of:

Daniel Schindler, School of Aquatic and Fishery Sciences, University of Washington
Daniel Selbie, Salmon Assessment and Freshwater Ecosystems Division, Science Branch, Fisheries and Oceans Canada
Peter Leavitt, Canada Research Chair in Environmental Change and Society, Department of Biology, University of Regina
Bruce Finney, Department of Biological Sciences, Idaho State University
Kim Hyatt, Salmon Assessment and Freshwater Ecosystems Division, Science Branch, Fisheries and Oceans Canada

Panel discussions were moderated by **Erland MacIsaac**, Salmon Assessment and Freshwater Ecosystems Division, Science Branch, Fisheries and Oceans Canada.

The panel discussion was started by posing the following questions.

- What are some of the key science messages from the paleoecological research to date?
- Are there new techniques and proxies we should be exploring?
- Where do paleoecological techniques work best for salmon reconstructions?
- How do we validate paleolimnological data?
- What are some of the applications of paleoecological data to ecosystem-based management of salmon?

Key Science Messages from the Paleoecological Research to Date

Paleotechniques are just another tool for researchers trying to understand sockeye salmon lake ecosystems. We can't expect paleo records to provide all the answers, or to answer key questions in all systems, particularly lakes with large, non-salmon nitrogen sources in their watershed, or in lakes with complicated sedimentary processes. Any study, paleolimnological or other, needs to be framed by the questions we are trying to answer.

As such, study design is key. Like any scientific experiment, a paleo study needs a contrast with a reference/control system. An in-lake story is less compelling without parallel data showing responses in a similar non-salmon system. Next, an estimate of whether salmon are likely to have a large forcing function on your system is needed. A preliminary nitrogen budget should indicate whether salmon provide a significant nitrogen signal, or may have in the past. Then we need to determine the sort of questions that can be answered given a lake's characteristics.

Constraints on salmon reconstructions will depend on applying a suite of approaches such as multiproxy methods, modelling, and control lakes. Interpretation of paleolimnological data from multidisciplinary proxies is rarely simple and may have more than one interpretation. Multiple proxies are necessary to correctly interpret and understand ecosystem patterns and experts in the various sub-disciplines of paleolimnology, salmon assessment and ecology need to work together to understand and interpret paleo data.

Researchers often expect paleo methods to work perfectly in every lake. They do in terms of formation of the sediment record, but the tools may reflect sensitivities to processes other than those of primary interest, and are often subject to a spectrum of influences. Paleoecology is a branch of systems ecology. It is a retrospective approach similar to historical data mining or retrospective modelling for understanding temporal trajectories. Retrospective studies are good when time is an important control, but not so good for identifying mechanisms. Researchers need to know whether a paleo study has the potential to answer the kinds of questions being asked.

Sedimentary Processes

Researchers also need to understand sedimentary processes in lakes and how they affect and alter signals in the paleo records. We often make assumptions about within-lake and watershed processes and need to be more rigorous about testing these assumptions on a lake by lake basis. What are the dissolved and particulate fluxes coming off the landscape of each lake? How are these materials being modified, transported and deposited within lake basins?

Escapement Data

The same issues apply to collecting and interpreting salmon escapement data. The poor quality of some escapement data is surprising to many paleolimnologists and this poses problems for calibrating proxies. Accuracy of long-term records depends on the range of enumeration techniques used, statistics, calibration methods, correction factors and the history behind the data. Most of the data for the big productive commercial sockeye stocks in Canada are long-time series and relatively reliable, but data quality for all 200 plus sockeye conservation units varies widely. Most systems aren't enumerated annually, methods change over time, and data quality can be quite poor. The task is to understand limitations and uncertainty in escapement data. More collaboration and integration among fisheries scientists, ecologists and paleo scientists is required to understand the limitations and apply escapement data.

Reference Systems

The choice of reference system is very important because the objective is to isolate the effects of salmonids on the sediment nitrogen signature. Invariant or wildly variable records in reference systems pose problems in interpreting salmon variability. Some parameters might be expected to covary between lakes through time if driven by climatic or environmental change. Invariant reference systems tend to make variability in the experimental lake look significant and widely variant systems make signal detection difficult. The best reference system is one that most closely matches the lake's limnological conditions except for the presence/absence of salmon. However, finding reference lakes in BC for whole lake fertilization experiments for sockeye has shown that spatial controls for time variant parameters and temporal controls for the spatial variations are both needed. It's a systems ecology problem and we're just at the point of defining what makes a good site and a good reference site for salmon reconstructions. Critical

discussion of these issues is a sign of an advancing, robust discipline. All sediment records contain important information on lake history, but this information may be less relevant for salmon reconstructions. In retrospect, it is not surprising that some attempts to reconstruct salmon histories have not been successful, given site characteristics such as salmon run size and nutrient budgets. Such applications may have thus cast doubt on the general applicability of paleo-salmon techniques. Based on lake characteristics across the broad spectrum of North American sockeye systems, it is likely that many sockeye salmon systems may not have salmon-nutrient loadings sufficient to produce strong sedimentary signals.

Applications to Ecosystem-Based Management

To apply paleoecological methods to ecosystem-based management, paleoecologists need well defined questions that are answerable using lake sediment records. The second challenge is to translate the science into messages that are understandable and useable by other ecologists and managers. For example, paleoecological data can be complex, often presented in multi-panelled graphics that may not be intuitive for non-paleoecologists to understand. Researchers also need to examine multiple proxies to crosscheck interpretations and determine the most likely story. Perhaps such detailed studies should be published in the primary paleoecology literature, before attempting to translate it into messages for managers.

Paloecology is often viewed as story-telling based on time series of different metrics and indicators, but the discipline may need to move more towards a framework of testing hypotheses and time-series data against alternative models developed from first principles or alternative management strategies.

Paleoecological data can tell us more than just historic estimates of fish abundance. The multi-proxy approaches can tell us about trophic interactions and primary production and this ancillary data can be useful for assessing habitat quality for salmon and ecosystem-based management.

Paleo data can be highly relevant and informative for fish management, but often has multiple interpretations. The story telling can sometimes brush lightly over contradictory information rather putting the data into a rigorous hypothesis testing framework. If there are alternative interpretations, these should be aired and weight-of-evidence or supplementary data should be used to eliminate competing hypotheses.

Paleolimnology is basically a technique, not a discipline with an overarching theory or framework to guide research towards testable questions. An example of applying paleo data to a hypothesis is "were prehistoric salmon densities higher than they are now?". Salmon biologists have to generate the theory that frames the hypotheses about how and why salmon populations change. Paleoecological techniques can be used within an experimental design, with reference systems, to test those hypotheses against competing models.

Where Do Paleoecological Techniques Work Best For Salmon Reconstructions?

Researchers have to consider processes important in forming the sedimentary record of their study site. Lakes filter environmental variability and climatic/watershed/ecological forcing agents influence their signals. One of the challenges for retrospective analyses is to use the measured signals to learn about processes. There are multiple sources of materials into a lake (from the air and watersheds) that are redistributed once within the lake. Every lake and depositional environment is different.

Lake sediments only collect particulates, and processes that affect or control the formation and transport of particles will affect interpretation of the sediment record. If a particular forcing function does not influence a particle, the record of such forcing will be difficult to interpret from sediments. Particulates deposited are further transformed in the sediments, leaving a residual signal reflecting the relative importance of the sources and the relative effects of the filtering mechanisms. For example, the relative contribution of terrestrial nitrogen is clearly important for salmon. Researchers need to be aware of boundary conditions, understand the mechanisms, and know how they and the lake environment may have changed over time.

Can the Paleo Record Shed Light on How Salmon Colonize Habitats and How They Will Respond to Large Scale Climate Changes?

Long cores from the marginal parts of the salmon distribution range may shed light on changes in marine-derived nutrients relevant to climate change. Paleo work may be the only method that can tell us about processes in the defined range of sockeye salmon and how that range may change with climate, similar to the tree ring approach of coring at forest climate margins. Archaeologists have suggested that salmon populations in the Columbia River system didn't reach levels that could sustain salmon-based cultures until 5-6000 years ago. Cores from the marine environment have documented long-term shifts in the abundances and ranges of salmon predators, like hake, that may play a role in climate effects on salmon marine survival and productivity particularly along their range.

On the other hand, we can only see the large, established salmon populations because the small populations important in colonization and salmon range expansion and contraction don't leave a signal in the sediment record. A population of a few thousand salmon can be quite healthy in terms of salmon population dynamics, but it will contribute little to the nutrient budget of the lake or show a signal that appears in a paleolimnology record. It may also be difficult to parse out precisely when colonization and environmental changes coincided if one is trying to determine timing and rates of colonization.

However, sockeye salmon have colonized and re-colonized habitats through multiple Quaternary glaciations, as have the other salmonids, but paleo techniques can only currently tell us about lake-rearing sockeye. The only question that we may be able to answer is whether there were large, productive lake-type populations of sockeye in the past. Large lake populations of sockeye may not be the primary source of early colonizers. Rather, there is evidence from studies of glacial recession lakes that river-type sockeye may be the primary colonizers. Ongoing studies in the Yukon may shed light on our ability to use coring methods to study sockeye colonization.

Are There Other Stable Isotopes or Proxies That Could Be Used as Alternatives to Nitrogen Isotope Data?

Contaminants may be one of the best proxies to develop powerful mixing models although the time series is relatively short. New analytical techniques are opening up a wider range of elements and isotopes that we can examine for ratio differences between marine and freshwater habitats that are incorporated into fish. Other isotopic models such as deuterium and oxygen can be indices of source waters for examining boundary conditions. Paleoecology has focussed on the relatively easy indices to get the story out, but the field is maturing and becoming more critical in terms of developing new techniques to complement existing methods. These can be powerful and have advanced the environmental and paleoclimate fields significantly.

Do Sedimentary Relationships Between C:N and δ15N Reflect a Terrestrial Signal or Could They Be Related to Shifts in Plankton Nutrient Limitation or Isotopic Fractionation?

Patterns of $\delta^{15}N$ and the carbon:nitrogen ratio in sediments across coastal BC lakes seem to show correlations with salmon abundance despite low nitrogen budget contributions from carcasses. However any regressions between sediment composition and salmon abundance across lakes can't be applied to down core data within a lake. Every lake will have its own pre-depositional processing that will affect the C:N ratio and $\delta^{15}N$ of its sediment. Another consideration is the dilution of salmon nitrogen in a bigger pool of lake nitrogen, which can correlate with lake flushing rates. In mixing models, a reference system is needed to set the watershed parameter. Best fits are those that include pairing of the signals through time to include the variation in the reference system. Using a model fitting approach can help us understand what parameters and processes best explain the data within and among lakes. The same model can be applied to other lakes but the parameters for the model that reflect pre-deposition processing will vary from lake to lake. Similar approaches have been taken with pigments. A goal of paleoecology is to be independent of the boundary data needed for interpretation; to be self referential and still correct with respect to mechanisms. Researchers don't need to measure the forcing function; if biological and biogeochemical processes are well understood, the mechanisms can be inferred.

Are There New Techniques, Proxies and Approaches We Should Be Exploring?

Compound-specific isotope techniques and other approaches to isolate specific compounds such as pigments and looking at their isotope signatures may be useful in glacial systems and lakes with large terrigenous inputs. This would be a significant methodological challenge as major effort and cost is required for technique development and subsequent analyses. Deuterium and oxygen hold promise as source water indicators. We also need to better define climate change, what it means in terms of mechanisms impacting and controlling lakes (e.g. temperature, precipitation, snowmelt, seasonality, etc.) and take a more process-oriented approach rather than a correlative one to understanding these ecosystems.

Climate processes also affect the marine environment and hence salmon survival in the ocean. This must be factored into the complications of trying to understand how sockeye salmon interact with their lake environment. Uncertainties about the role of freshwater processes on marine recruitment of spawners and the potential for marine processes to override the freshwater environment need to be considered. Canadian federal departments are now obligated to manage for optimizing multiple species objectives under an ecosystem-based management paradigm. Knowing the impacts of salmon on freshwater ecosystems and the impacts of the ecosystem on salmon are equally important parts of the bigger picture. We can utilize paleo insight and techniques that are affordable, reliable, repeatable, and informative for that approach. Some paleo indicators currently meet all those criteria while others don't and require further development. For example, in British Columbia there are over 200 sockeye conservation units with about two-thirds in the poorly resolved coastal zone, and we have little relevant ecosystem data to manage them. Paleo techniques may offer an opportunity to collect useful retrospective data although they are not necessarily easy or fast (e.g. diatoms, zooplankton, geochemistry).

Conveying Paleoecological Information to Other Practitioners, Managers and the General Public.

Presenting results clearly and with appropriate qualifiers is key to ensuring that data and methods are not misapplied or misunderstood. It is important to state what is known, what is not known and the underlying assumptions that are used in drawing conclusions. It may appear that there is not yet consensus about the techniques and interpretations, but that is just a reflection of the evolving development of the science.

The ability to use paleo techniques to go back in time well beyond the limited historical records is an intriguing aspect of the field, but multi-proxy methods are time-consuming and costly so it is essential to apply resources to productive studies. Managers need to compare paleoecological data to the costs and constraints of long-term fish population monitoring to be convinced that paleotechniques are worth the high short-term investment. This workshop is a step towards addressing these challenges. Concerted efforts and funding will be required to advance paleo techniques and interpretation, and their integration into management.

KEY RECOMMENDATIONS

- Formulate questions about sockeye salmon ecology that a paleoecological study of a nursery lake can realistically answer; paleoecological data is good for temporal trends but weak on ecological mechanisms.

- Paleolimnological techniques that are reliable, repeatable, and informative can contribute to ecosystem-based management of sockeye salmon by testing hypotheses against competing models of how and why salmon populations change, and the interactions between salmon and their freshwater and marine ecosystems.

- The most informative study designs use multi-proxy suites of physical, chemical and biological paleoindicators with appropriate reference lakes and well documented lake and watershed characterizations.

- Partnering between paleoecologists and fisheries ecologists is required to ensure the limitations of historic salmon population data are correctly integrated into the paleoecological interpretations.

- Preliminary nitrogen budgets can determine whether salmon contribute enough of the nitrogen loading to a lake ecosystem to leave a detectable $\delta^{15}N$ signal in the sediment cores.

- Interpreting the $\delta^{15}N$ paleorecord for salmon escapement requires a reference system and the fitting of nitrogen mixing models in order to understand what parameters and processes best explain the data within and among lakes.

- A better understanding of how variations in sediment deposition and filtering processes alter the paleo record in a given lake is required to interpret variations in sediment signals.

- Paleolimnological techniques may only be informative about the post-glacial histories of large, lake-resident sockeye populations and not smaller, lake and river populations that may be the primary habitat colonizers.

- Analysis of contaminants, other biogeochemical proxies in sediments, and new analytical techniques for salmon-specific and source water isotopes and elements show promise to greatly enhance the toolsets for paleoecological studies of sockeye lakes.

- Effective communication of the benefits and limitations of paleoecological information needs to be clearly conveyed to managers so they can weigh paleoecological approaches against the costs and constraints of long-term fish population monitoring and be convinced that paleotechniques are worth the high, short-term investment.

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